

THE TELEROBOT TESTBED: AN ARCHITECTURE FOR REMOTE SERVICING

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ABSTRACT

The NASA/OAST Telerobot Testbed will reach its next increment in development by the end of FY'89. The testbed will have the capability for: force reflection in teleoperation, shared control, traded control, operator designate and relative update. These five capabilities will be shown in a module release and exchange operation using mockups of ORUs. This development of the testbed shows examples of the technologies needed for remote servicing, particularly under conditions of delay in transmissions to the servicing site. In this paper the following topics are presented: the system architecture of the testbed which incorporates these telerobotic technologies for servicing, the implementation of the five capabilities and the operation with the ORU mockups.

INTRODUCTION

From its inception the NASA/OAST telerobot testbed project has been asked to investigate the technologies in the disciplines of telepresence, robotics and artificial intelligence in application to remote servicing. The technologies chosen for integration, system test and demonstration in the testbed have the potential to usefully complement, significantly enhance or even replace selected manned space activities through engineering development and qualification in flight telerobotic systems. Indicative of this potential, certain generic tasks, suggestive of space assembly, maintenance and repair, are performed in the testbed. Through performance in several modes: direct teleoperation with/without force reflection, shared control, traded control between teleoperation and the autonomous system, and robotic operation, the benefits of the individual technology contributions to the operation can be quantized and recommendations for use in telerobotic systems established. This paper reports on the development leading to the first such quantization, using an ORU removal/replacement task. Several recommendations are offered for near-term telerobot system developments, based on the experience of this testbed project.

ISSUES IN REMOTE SERVICING BY TELEROBOTS

In considering the use of telerobotic systems in remote servicing operations several factors will guide the application. These factors form an initial set of system requirements and are derived from the experience base of manned space servicing operations.

Telerobots must work in the same domain as astronauts in EVA

For the near future, the opportunities for remote servicing of spacecraft will be limited to those spacecraft designed for service by astronauts in EVA. Consequently, telerobots must be designed to work with the fixtures and devices of ORU's, fluid couplers, hand holds and tools for astronaut servicing. Options for robot friendly designs will be limited to such as: end-effector attachment accommodation for tools and hand holds, LED type markings for object tracking by camera/laser systems, and power and signal ports for attachment of the telerobot. Fixturing and jiggling of the worksite, a common practice for industrial robots, will be restricted to new operations for the telerobot such as assembly.

Additional complexity for the telerobot will be afforded by the environment at the worksite for service. Experience in past servicing missions has shown this environment to be variably if not poorly lit (by present day robotic laboratory standards) with restriction on access or obstacle strewn.

Telerobots must be capable of adapting to changes in the workplan

The history of manned servicing missions (e.g., Solar Max, Syncom 3, see [4] also [7]) has shown that well planned and rehearsed servicing procedures must be adapted to accommodate the unexpected. The telerobot performing a servicing mission must exhibit some of the same flexibility of an astronaut in EVA to adapt to errors in modeled behavior and develop workaround procedures.

A human operator must be able to supervise telerobots in operation

The presence of a human supervisor for a telerobot is inherited from the history of space operations. In early applications of telerobots to servicing in which telerobots must work along side astronauts in EVA, such supervisors will have a special responsibility for safety at the worksite for both the astronaut and the serviced item. Another dimension is added to this role when the supervisor acts as the operator of a telerobot system. A human operator is an essential component of a telerobot system from the commanding of the movement of manipulator arms through hand controllers to the establishing of frames of reference for and initiation of robotic operations. The flexibility in telerobot systems for adapting to unexpected conditions and developing workaround procedures will be the special contribution of the operator.

As a consequence there will be requirements for telerobot systems to provide a rich set of data feedback sources to the operator remotely located from the worksite. These sources (e.g., cameras, ranging systems, force/torque sensors, additional lights) will be additions to that nominally provided for monitoring and recording the activities of astronaut servicing in EVA.

Telerobots must be capable of performing a variety of tasks at different worksites

Past servicing missions have required the performance of a number of tasks by the astronaut. Although a primary task may be the removal and replacement of an electronics or instrument module (e.g., Solar Max), access to the module required removal/cutting of thermal blankets, release of threaded fasteners, detachment of electrical connectors, movement of the module around wire bundles and alignment/checkout of the replacement module. Servicing at more than a single site (or in the case of Solar Max more than a single side of the satellite) has also been a requirement. For a telerobot this implies that the system must be capable of establishing a frame of reference, updating that reference during the operation and performing a number of different manipulations at any such site.

Telerobots must be capable of operating under conditions of delay in transmission

The earliest missions for a telerobot will be service based at the STS orbiter or the Space Station, where the human operator will be an astronaut in IVA. The full potential for the contribution of telerobots will be realized with the expansion of operations to servicing missions remote from manned vehicles. In these instances, transmissions to the human operator, in all likelihood located at an earth-bound station, will be relayed through communication satellites and thus subject to variable delay on the order of 2-6 seconds. Maintaining the rich set of feedback for human interaction with the telerobot under these conditions will be the challenge.

In the following paragraphs the approach in the telerobot testbed project to meeting these system requirements for a

servicing telerobot is discussed.

TELEROBOT TESTBED CAPABILITIES

The approach adopted by the first applications of telerobots to meeting the requirements of remote servicing will use forms of direct teleoperation with forces/torques reflected to the operator. Of the many types of developments possible, both the servicing telerobot for the Space Station, the Flight Telerobot Servicer (see [2]), and the telerobot testbed have chosen to implement a Cartesian or task space based system. The telerobot testbed approach is discussed below.

Force reflection in teleoperation

In a task space based teleoperation system the operator controls the manipulators by providing six position/orientation commands for the location of the end effector through a six degree-of-freedom hand controller. The electronics of the system develop the individual manipulator joint level commands necessary to drive the end effector to assume the commanded position, resolving any configuration ambiguity as necessary. Manipulator path planning, collision avoidance, arm coordination and object manipulation are all performed by the operator in real time through the hand controllers. The feedback to the operator of the effect of his manipulation is provided by the kinesthetic of the hand controller back driven by the input from force/torque sensors. In the testbed system, these sensors are mounted on the wrists of the manipulator and measure the forces and torques encountered by the end effector in contact at the worksite. The six forces and torques so measured are transformed into the commands suitable to back drive each of the joints of the hand controller.

Given the task space reference for such a system, there is a natural way for the hand controller to be referenced so that manipulation by a tool can be performed in the same style as that by the end-effector. The hand controller can also have a smaller kinematic and dynamic range than the manipulator, affording a compact configuration of the operator workstation. These capabilities are provided by the functions of the system to accept a change to the coordinate frame of reference, to be indexed and scaled.

The performance of such a force reflecting teleoperation system has been recently characterized (see [3]) in terms of the latency in the round-trip passage of data in the system. By round-trip passage is meant the transmission of (a) data derived from the input to the hand controller, to (b) data which commands the joints of the manipulator to achieve a new position, to (c) data which is measured from the force/torque sensor, to (d) data which is used to back drive the hand controller. When the latency of this round-trip passage of data is under 10 ms the operator has an adequate 'feel' of the end effector in contact with the work site. Furthermore, as measured through time for manipulation, training and sum of forces applied during the task, the 10 ms threshold represents a clear performance boundary.

When because of delays in transmission or limitation in implementation the latency increases above this threshold, other forms of telerobotic operation should be considered for a servicing application. One such is shared control as discussed next.

Shared control

In a general sense, shared control allows for manipulator control to be jointly performed in real time by both an operator in teleoperation and an autonomous system. In the telerobot testbed two examples of such shared control are being developed. In the first such example, the location of an object grasped by two manipulator arms is controlled through the inputs from a single hand controller. The autonomous control of the telerobot modulates the forces applied by the manipulators to the object with the goal of minimizing the net force. This control is exercised in real time with the control which results in the repositioning of the object under control of the operator. In the second example, the location of the end effector is controlled by the input from a hand controller. When in contact with the environment, the forces encountered are measured by the force/torque sensor and the autonomous control reacts to these forces in a position accommodation scheme. During a particular task, the operator is responsible for maintaining the end effector in position at the worksite. The autonomous system prevents inadvertent or extreme forces from being applied through the position accommodation control.

It is this latter example of shared control which suggests the approach to conditions in which a telerobot in servicing experiences latency in data transmission which prevents effective force reflection in teleoperation. In a shared control mode the telerobot's autonomous system can modulate or otherwise control the amount of force/torque applied during a task. The risk of damage from binding, galling, gauging or other inadvertent force application to satellite equipment can be mitigated when the operator may otherwise be unable to sense the extent of forces introduced by the telerobot.

When the latency in data transmissions begins to reach 1-2 seconds video and other forms of operator feedback begin to degrade. The delay in tracking the position of the manipulator arms and end effectors can result in inadvertent collisions with equipment at the worksite. For gross motions of the manipulators, this problem may be handled through the use of preview displays. In such a system, the motion of the hand controllers drives a simulation display of the manipulators overlaying the video feedback. The operator gets a preview of the effect of the motion of the arms through this display and can correct for potential collisions with the worksite. This technique of preview display cannot account for conditions in which the arms are already in contact with the worksite, since simulations of contact forces and mechanical compliance by the arms will be prone to error given reliance on geometric and dynamic models of the arms and the workpieces. Other types of telerobotic operations should be considered under conditions of this size latency. One approach taken by the telerobot testbed is a form of traded control discussed next.

Traded control

In the most general sense, traded control is the transfer of control between the operator in teleoperation and the autonomous control capability of the telerobot. In the telerobot testbed, the operator performs all gross motion planning and maneuvering of the end effector to the vicinity of a task at the worksite. The operator then transfers control to the autonomous system for motion of the end effector to contact with the worksite and subsequent performance of work. During this period the operator commands actions of the telerobot in a supervisory mode, maintaining the capability to intervene at any time to correct and/or stop the manipulation. When the work is completed, as judged by the operator, the system moves the arm/end effector away from the worksite and offers to transfer control to the operator for subsequent teleoperation.

Although this style of traded control is intended as a form of telerobotic operation which accommodates 1-2 second latency in transmission, this type of operation can be used effectively in conditions of restricted visual feedback to the operator. Autonomous alignments, contacts, seatings of end effectors and tools can be used to augment a basically teleoperated manipulation through forms of traded control. Traded control can work so long as the autonomous manipulations performed prove successful. Given reliance of this control on the models of the task, worksite and manipulators, techniques for accommodating errors in these models must be present to ensure success in the operations. The following two paragraphs present such techniques developed in the telerobot testbed.

Operator designate

For subsequent manipulation the operator can register the location and otherwise identify an object using the function of operator designate. In the telerobot testbed this function is implemented using a wire frame model of the object in an overlay of the video feedback from the worksite. The operator assigns, in a one-by-one fashion, the vertices of the model to the vertices of the object in the video. When sufficient vertices have been assigned, the system calculates the size and position of the object in the camera view using the models of the camera providing the image. By performing the operation in more than one camera view, (assuming sufficient separation of the cameras) a six dimensional vector giving the location of the object can be developed. The location and name of the object are registered in the autonomous systems data base for future manipulation. By a similar technique, regions of space at the worksite can be designated as 'forbidden' regions, thus enhancing avoidance of inadvertent collisions. Parts of the telerobot can also be designated, allowing for combined registration of the camera and arm models.

Since the object and telerobot will be moved during servicing operations the operator designate function allows the operator and thence the autonomous system to track the present locations of objects. This function does rely upon good camera models since the object so designated is registered in an absolute sense at the worksite. In the next paragraph this restriction is relaxed.

Relative update.

In a relative update to the data base of the autonomous system, the operator locates two objects at the worksite and calculates the distance between the objects. When the two objects are a workpiece and the end effector of a manipulator arm, the distance between the objects can be used to command the arm to contact with the workpiece. In the first application of this technique in the telerobot testbed, the operator designates the two objects. In a variation, a machine vision function can be used to provide the locations of the objects.

Since the calculation of the distance between the objects is performed essentially in the image buffer of the video, a precise camera model is not needed. The resolution is provided to the pixel level. By calculating in several views, a six dimensional frame vector can be developed affording the information necessary for grasps and other manipulations.

These five capabilities of the telerobot testbed yield an approach to the implementation of a telerobot for remote servicing. In the following the architecture which is an implementation of these capabilities is presented.

TESTBED ARCHITECTURE

Conceptually, the telerobot testbed architecture follows a hierarchical design philosophy. In this design the human operator and machine intelligent functions of the system are placed at the top of the architecture with the primitive or mechanical functions toward the bottom (see Figure 1). Five subsystems comprise the testbed system. A brief description of the functions each follows (see also [1])

Operator Control Station (OCS)

The OCS provides an efficient user friendly physical interface between the operator of the telerobot and the testbed system. An interface for two operators is in fact provided. For the operator of the telerobot a stereo display, a pair of 6 degree-of-freedom force reflecting hand controllers, graphical displays of the force/torque sensor measurements and monitors to the computer system of the OCS and the TPR (see below). A voice recognition system allows the operator to control the telerobot autonomous functions while controlling the telerobot manipulators through the hand controllers. An enunciator provides verification of input commands and status of progress of the system in operation.

A pair of video displays, a monitor to all telerobot subsystems, and a set of function switches for control of the OCS are provided for the second operator, the test conductor. This operator monitors the performance of the telerobot operator and the telerobot system during operation and sets up test conditions.

At the OCS the operator initiates all functions of the testbed. In particular, the function of operator designate is performed using the video displays at the OCS.

Task Planning and Reasoning (TPR)

The TPR performs functions of high level task planning and gross motion planning. In supporting the five capabilities of the testbed a menu for operator commanding of the autonomous functions of the system is provided. A kinematic simulator can be used to preview the effect of an operator initiated command.

The TPR also provides a data base of objects in the worksite, including their locations, connectivity and semantic relationships. During the testbed operations of operator designate and relative update, the TPR interacts with the OCS to update the data base with the locations of objects at the worksite. During autonomous operations in a trade of control, the data generated by the functioning of the sensing and manipulation capabilities of the system is assembled by the RTC for update of the TPR data base. When applicable, the data associated with an update is processed for spatial and semantic consistency.

Run-Time Control (RTC)

The RTC provides the fine motion planning and execution of autonomous operations by the telerobot. The RTC sets up the sensing and manipulation functions in the testbed for autonomous operation or teleoperation. RTC monitors execution and interacts through the TPR with the operator to direct recovery in case of failure.

As a part of the fine motion planning, the RTC contains a kinematics simulator which plans motions of the manipulators to avoid joint stops and singularities. A run-time data base of the locations of objects at the worksite is updated during operations and is used to plan for detection and avoidance of collisions. Knowledge of the kinematic, dynamic and inertial properties of the manipulator arms and objects to be manipulated is kept as part of this data base.

Sensing and Perception (S&P)

The S&P contains the cameras and the machine vision functions of the testbed. These functions include a tracker for use in supply position/orientation of objects in the worksite. This tracker employs a model matching technique like that of the operator designate function using the images of an object in several views to derive a six vector of location. Although developed for tracking moving objects at the worksite, in supporting the five capabilities of the testbed, the tracker is used to determine locations of stationary objects in the worksite. The data from operator designate is used as an initial estimate of the location of the object in this function. The tracker performs a refinement on the location of the object, employing statistical correlation techniques to more precisely match model to image of the object. The data so developed can be used both in an absolute or relative mode for a subsequent manipulation.

Manipulation and Control Mechanization (MCM)

The MCM provides the manipulation capability of the testbed. This subsystem consists of three 6 degree-of-freedom arms, one of which serves as a camera platform, two servo controlled end effectors, the electronics and computing system which supports the data rates necessary for force reflection in teleoperation and both the autonomous and shared control capabilities of the telerobot. These latter functions of the MCM are provided through a set of macros, software routines instantiated by the data provided either by the autonomous system or the operator to perform certain manipulation skills.

One of the requirements for the development of the testbed system is the ability to accommodate growth. This is provided in part through the loose confederation of computing systems which comprises the testbed (see Figure 2). The use of a network for the basic intercommunication architecture allows easy expansion through the addition of computing resources. In addition, the existing computing systems can be arranged to form different telerobot configurations. One such configuration will be formed with the testbed accommodation of time delay. In one example, the OCS/TPR will be considered the local site and the RTC/S&P/MCM considered the remote site. With the buffering of commands from the OCS/TPR along the network and through the teleoperation system, a sense of latency in data transmission can be given to the operator.

Finally, the demonstration of the five capabilities of the telerobot testbed will be provided through an ORU removal/replacement task (see Figure 3). In this task, the site for placement of an ORU mockup (called the truss structure of the stow bin) will be moved to some location within the reach envelope of the manipulators. The operator will attempt to remove the module from a platform between the arms and insert it into the truss structure. The operator will be asked to first do the task in force reflecting teleoperation. Then the operator will perform the task using the functions of operator designate (locate the ORU and the place for insertion), relative update (determine the distance between the end effector of the arm and a grapple lug on the module, or the distance between the module and the place for insertion), and traded control (the operator moves an arm near the grapple location and trades to the autonomous system to grasp, or the operator moves the arm near the insertion point and trades to the autonomous system to perform the insertion). Lastly, the operator will be asked to repeat the operation using shared control. Each of these manipulations will be repeated under condition of 2 second latency in data transmission. In a separate demonstration the dual arm manipulation capability of the testbed will be shown using another ORU mockup.

DIRECTIONS FOR DEVELOPMENT

During the four year development of the telerobot testbed the experience of integration has led to certain choices in the utilization of the technologies in telerobotics based on the relative maturity of the technology for near term application and suggested by the environment for remote

servicing. These choices are described below in the form of recommendations for development of a telerobot to perform servicing in a quasi-static environment (i.e., at a worksite where change in configurations is only introduced by the telerobot).

Human vision through operator designate can replace machine vision

In the earliest applications of the machine vision function of fixture verification (i.e., refining the knowledge of the location of a fixed object in the worksite) in the testbed, accuracies on the order of 2mm in position and 0.5 deg in orientation were achieved in locating an object in the worksite from a camera located within 1m of the object. Such update of the location of an object was required to ensure a successful grasp or other manipulation where clearances between gripper finger and object of ± 2.5 mm were common. In order for the function to work, an accurate camera model and an initial acquisition of the object was required to allow the machine vision algorithms to converge reliably on the desired object. In the testbed the acquisition was provided through an a priori generated data base which, with calibration, was accurate to within 5mm of the correct position. The accurate camera model was provided through a careful calibration of the camera platform (a PUMA arm) and camera.

Given the difficulties of obtaining much less maintaining a well calibrated model of the worksite or of the cameras in a remote servicing application, other approaches were considered for this latest integration of the testbed. The operator designate function with accuracies in locating the position of an object to 1cm from a distance of 3-4m would be sufficient for reaching the acquisition range of a fixture verification function. The relative update function with accuracies of ± 3 mm from a distance of 1m would be sufficient to substitute for the data from the fixture verification function. In the latest testbed integration, this latter statement is particularly true since clearance requirements between gripper finger and object are at least ± 1 cm. It should be noted that several centimeters of clearance are nominally required for astronaut in EVA grasp or manipulation of servicable items [6].

Relative update can compensate for uncalibrated camera views

In supporting the machine vision fixture verification function, the requirement for a calibrated camera model involved both calibration of the camera platform (a PUMA arm) and camera. Such calibration must be performed at a number of positions to minimize the 'drift' associated with non-linearities in mechanical devices vis-a-vis linear models for the platform and focal plane. In the testbed 1-2cm errors in absolute position and 2-3 degrees of error in absolute orientation knowledge have been observed when relying on knowledge of platform (arm) kinematics and a camera model derived in a single position camera position. In a remote servicing application, although such calibration is a ground-based function, the requirement for relocation of the telerobot at the worksite and the inevitable uncertainties in a priori models make it impossible to expect millimeter accuracies from functions requiring

calibration. The ± 3 mm accuracy in knowledge of locations between two objects reported from the relative update function has been observed in a number of camera positions in the worksite using a camera model derived in a single camera position.

Substitute human teleoperation for machine-based global path planning

Automatic planning of arm motions through the worksite requires knowledge of the location of objects as obstacles to avoid unwanted collisions with the arms. In general this is a large volume with potentially a number of objects which must be modeled, located with precision and tracked for motions during manipulations. The path planning problem is also complicated by the presence of redundant degrees of freedom for the manipulator or through a manipulator positioning system (e.g., FTS [2]). Automatic planning for such systems requires some knowledge of the task to be performed or other suboptimal constraint (e.g., position and lock of an elbow joint) to assist in selection of one solution from the many possible.

By relying on the operator to position the arms through a teleoperation function, a telerobot system does not require models of the entire worksite and relies on the operator to resolve any positional ambiguity due to the presence of redundant degrees of freedom.

Retain machine-based local path planning

The problems associated with global path planning are not as severe for local path planning: that planning of arm motions through a volume from 10's of centimeters distance until contact with the worksite. In such cases knowledge of location for a few objects is required. Such knowledge can be accurately acquired through use of operator designate and relative update. The planning of arm motions is somewhat simplified given that the resolution of ambiguity with redundant degrees of freedoms can be assumed performed through the operator teleoperation function. Lastly, the operator's visual feedback can be most restricted in near contact conditions with the worksite, making further direct teleoperation difficult if not impossible in operations with data latency on the order of a few seconds.

Although these conclusions about the use of telerobotics in remote servicing can help guide early applications of the technology, this is far from the last word on the subject. In applications where millimeter-level precision is required, a machine vision function will be better at deriving position than a human operator. In dynamically changing conditions (e.g., multiple arms/telerobots or astronauts in EVA with telerobots working at the same site) automatic tracking of locations can prevent unwanted if not unsafe collisions. With clutter in the worksite, it may not be obvious what constitutes a collision-free path through the worksite. An automatic spatial planner, used perhaps in an advisory capacity for subsequent teleoperation, can assist the operator to plan motions through the worksite. Lastly, many of the techniques discussed above rely upon an arm which can be accurately controlled, through autonomous

techniques or teleoperation, to negotiate the final few millimeters and self correct through sensory feedback from encoders, force/torque sensors, etc. to allow for grasps, insertions or other manipulations. Although achievable with arms built for the commercial sector, this will, in itself, be a technology challenge in the development of a flight qualified arm which will enable the use of telerobotics for remote servicing.

CONCLUSION

This paper describes the capability of the NASA/OAST telerobot testbed in the performance of certain generic tasks, suggestive of the space assembly, maintenance and repair operations of remote servicing. Through performance in several modes: direct teleoperation with/without force reflection, shared control, traded control between teleoperation and the autonomous system, and robotic operation, the benefits of the individual technology contributions to the operation can be quantized and recommendations for use in telerobotic systems established. The development of the testbed leading to the first such quantization, using an ORU removal/replacement task, is reported. Several recommendations are offered for near-term telerobot system development, based on the experience of this testbed project.

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SYSTEM FUNCTIONAL BLOCK DIAGRAM

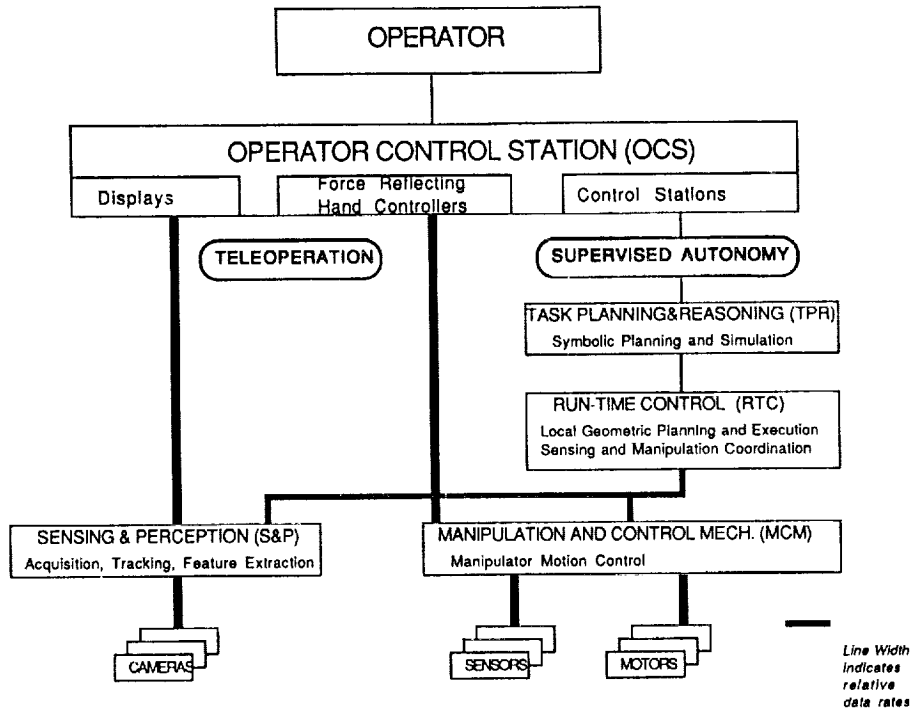


FIGURE 1

THE TELEROBOT TESTBED: AN ARCHITECTURE FOR REMOTE SERVICING

System Computing Architecture

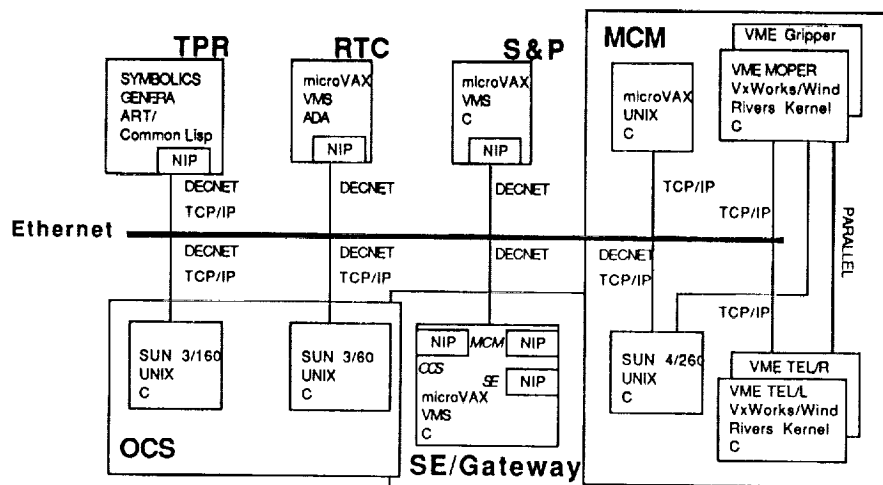


FIGURE 2

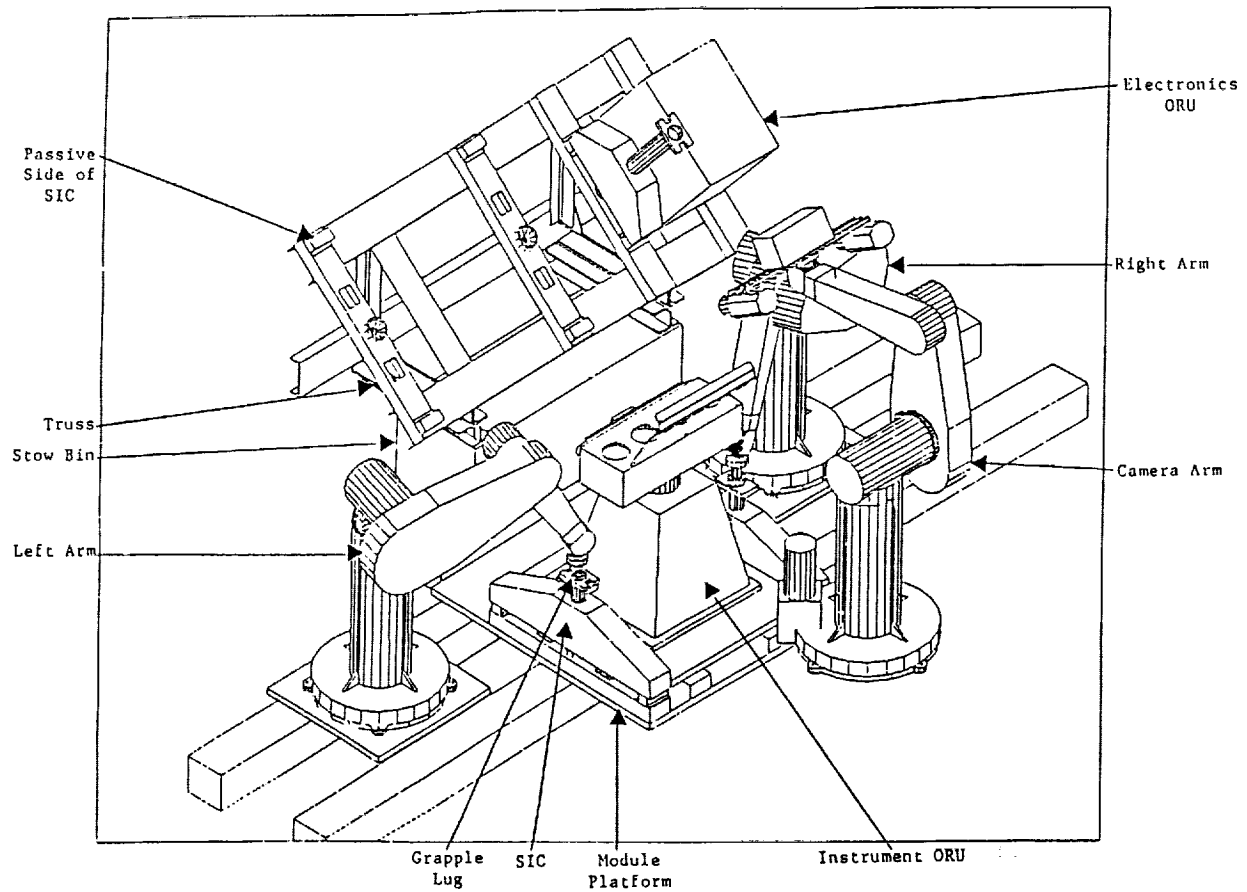


FIGURE 3